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Autonomous Heat Production from Solar Concentrator

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Abstract

From a promising first study performed on a reflecting slats solar concentrator, we propose to improve and optimize the design by providing a number of additional functions related to technological progress in the field of solar energy and electrical engineering. In order to satisfy a need for a specific production of heat around 150°C, the original system is equipped with an anti-radiation structure boiler and a more efficient control to improve and regulate the production of heat. Taking advantage of these technical improvements, photovoltaic cells are added behind slats for a stand-alone function and a possible connection to the grid (Figure 1). This new approach of solar concentration with hybrid PV/Th is being studied with an experimental system designed by our research laboratory.

Concentrating heating, photovoltaic supply, solar hybrid collector, tracking

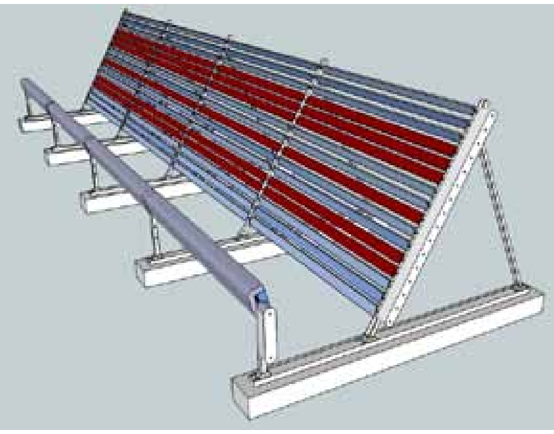

Fig. 1. Hybrid solar concentrator (SRLO).

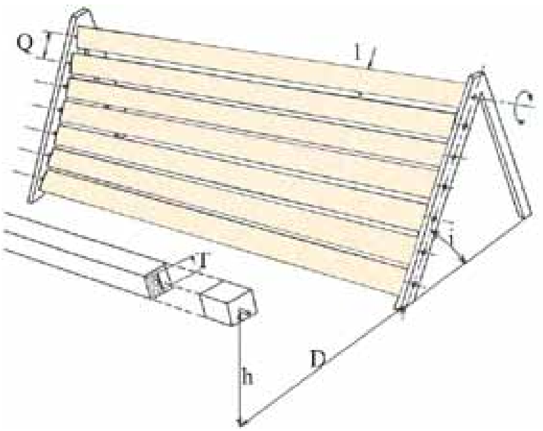

Fig. 2. Main parameters of the reflecting structure.

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1. Introduction

The original concept was intended for developing countries to satisfy a need of heat to medium temperature (120-150°C). The structure of the system should be simple, robust, portable and cheap [1]. This specific collector use several reflecting slats, oriented East/West and partially tracking the sun by rotation around one axis (Fig. 1). The system produces a concentration onto a boiler for an heliothermal conversion use. The goal is to provide a heat source of a constant quality level close to 150°C. To do so, an automatic control of slats rotation is necessary to focus the reflected solar radiation on the boiler throughout the day. A first experimentation was initiated in the renewable energy research center of University of Corsica [2]. To improve the system it is now necessary to optimize its operation and obtain heat at a temperature as close as possible to the set point and without auxiliary energy source.

Nomenclature

h, height of the boiler (m) ; **T**, width of the boiler (m) ; **D**, distance from the boiler to the fixed frame (m)
i, angle between the frame and the horizontal plane (rad) ; **l**, width of a flat reflecting area (m)
L, length of a flat reflecting area and a boiler unit (m) ; **hi**, height of the i flat reflecting area (m)
Q, distance between two consecutive flats (m) ; **N**, number of flats ; **Sr**, total reflecting area (m^2)
Sa, total absorbing area (m^2) ; **C**, geometrical concentration rate ; **φ**, latitude (rad)
Lg, site longitude (rad) ; **Lg_{st}**, standard longitude (rad) ; **dn**, number of the day ; **Γ**, daily angle (rad)
ST, solar time (mn) ; **LT**, local time (mn) ; **Et**, equation of time (mn) ; **Δ**, additional summer time (mn)
α, elevation of the sun (rad) ; **ψ**, azimuth of the sun (rad) ; **δ**, declination of the sun (rad)
ω, hourly angle (rad) ; **γ**, tilt angle of the boiler/vertical (rad) ; **β**, tilt angle of the mirror/vertical (rad)

2. Study

2.1. Original concentrator

A first study [3], [4] established that this system can be defined according seven parameters (Fig. 2):
T, h, D, Q, i, N, l.

A prototype was built with 4 coupled units of concentration, that is to say 64 mirrors (L=2.42 m; l=0.1 m) constituting a total reflecting area Sr=15.488 m^2 and 4 boilers (L=2.42 m; T=0.15 m) connected in series giving a total absorbing area Sa=1.452 m^2. This determines the geometrical concentration rate C=10.66 [5]. Each slat was equipped with pulleys and all slats were moved in the same time by an electric jack driven by an electronic command control that calculated in reel time the angle of mirrors.

2.2. Astronomic equations

In order to enslave the mirrors and always concentrate it on the boiler, the controller must know in real time the sun elevation and azimuth. From the date and time it calculated the following parameters [6]:

Daily angle

$$\Gamma = \frac{2\pi \cdot (\mathrm{dn} - 1)}{365}$$

Solar time

$$\mathrm{ST} = \mathrm{LT} - \Delta - 4 \cdot (\mathrm{Lg} - \mathrm{Lg}_{st}) + \mathrm{Et} \qquad (1), (2)$$

Elevation of the sun

$$\alpha = \mathrm{asin}(\cos(\varphi) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\varphi) \cdot \sin(\delta))$$

Azimuth of the sun

$$\psi = \mathrm{asin}\left(\frac{\cos(\delta) \cdot \sin(\omega)}{\cos(\alpha)}\right) \qquad (3), (4)$$

2.3. Equations of SRLO

The normal of the mirror moving in the vertical plane parallel to the south, it is necessary to express the projection of α in this plan (Fig. 3):

$$\alpha p = a\tan\left(\frac{\tan(\alpha)}{\cos(\psi)}\right) \quad (5)$$

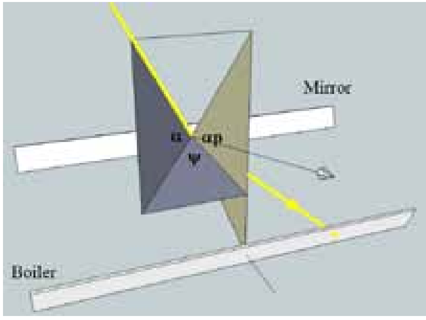

Fig. 3. Projection of sun elevation.

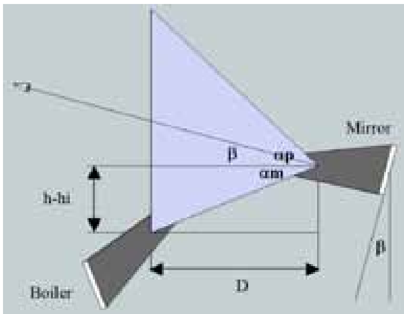

Fig. 4. Tilt of the mirror.

As shown in figure 4, for focusing the reflected radiation on the boiler, the Descartes relationship must be verified by the mirror tilt:

$$\beta = \frac{\alpha p + \alpha m}{2} \quad \textit{with} \quad \alpha m = a\tan\left(\frac{h - hi}{D}\right) \quad (6), (7)$$

To determine the best position of the boiler and the reflecting structure angle, it is necessary to calculate the deviation of the spot. It will allow to take account the part of energy lost by this effect. In the first time, it needs to calculate the projection of the sun azimuth:

$$\psi p = a\sin\left(\cos(\alpha)\cdot\sin(\psi)\right) \qquad Dev = \tan(\psi p)\cdot\cos(\alpha m)\cdot D \quad (8), (9)$$

In the last time, we can calculate the spot width according the boiler tilt:

$$La = \frac{\cos(\beta - \alpha m)}{\cos(\gamma + \alpha m)}\cdot L \quad (10)$$

A computer program was developed [7]. It gives for each minute and each day of the year the spot width on the boiler, the geometric concentration in the same time and the quantity of energy harvested per square meter of mirrors based on a typical weather year. The relationship between collectible radiation and radiation type gives the geometrical concentrator efficiency. By calculating the geometrical concentration, the boiler width is taken equal to the focal width spot. When computing the focal spot width the opening angle under which the solar disk is seen is taken into account (0.0095 Rad), manufacturing tolerances and pointing mirror precisions. The width of the focal spot and the geometrical concentration are closely linked but the greatest concentration does not always match to the smaller spot according some parameters variation. In this case, optimization was done on the concentration. There are no simple methods giving better optimization of two criteria that depend on seven parameters. The optimization was done separately on each item starting with those who seemed the most sensitive. Several "passages" as in the method of convergence was necessary before reaching a satisfactory geometry. Technological imperatives have arbitrarily limited the range of variation of certain parameters like the number of mirrors and their minimum width or height of the boiler. Given all these reservations and according to the latitude where the system operates, a compromise was found and it is from these data that the concentrator is performed:

$$T = 0.15m \; ; \; Q = 0.125m \; ; \; D = 1m \; ; \; i = 60 \; ; \; h = 0.5m \; ; \; N = 16 \; ; \; l = 0.1m$$

2.4. Original Boiler

Four linear boilers has been installed and connected in series in a primary loop circuit [8]. You will find the description of these boilers in the figure below:

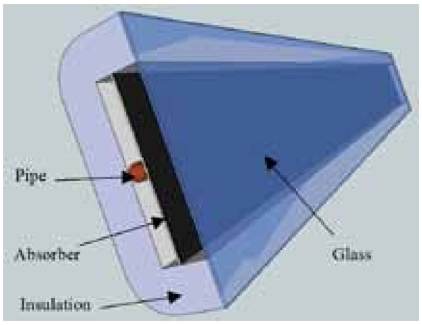

Fig. 5. Flat plat boiler with greenhouse effect.

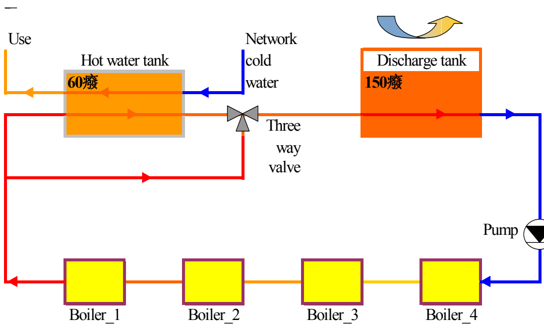

Fig. 6. Original primary loop.

The primary loop was built and connected to two storage tanks. One is insulated and produces hot water at 60°C. The other is not insulated and is used to simulate the load at 150°C. A three-way valve bypasses the solar tank when it reaches the set point. Then the loop runs only on the load (Fig. 6).

2.5. Discussion

In this configuration, the reflective system with this simple primary loop is well sized and is able to quickly reach the set temperature of 150°C under normal weather conditions. However, some elements of this system require a power source to operate:

jacks (230V, 60W) ; pump (230V, 100W) ; three-way valve (230V, 6W)

So it is not portable and therefore cannot be used in emergency situations and in remote network locations. The enslavement of mirrors operating in “stop and go”. When the high temperature set point is exceeded the action of the jack defocuses all mirrors. The focus is running again when the record low is detected. The hysteresis setting is difficult to control because all the spots moves and causes high variation of power. The primary loop provides very little flexibility. Even if the series arrangement of boilers enhances the quality and therefore the energy level of the highest temperature, there is no way to enslave it. If direct radiation is not enough it is not possible to act on the pump operating at constant flow. In addition, pressure losses are greatest in this type of configuration.

3. The SRLO upgrade

3.1. Reflective structure

The aim being to provide heat at constant temperature in all circumstances; we have equipped the rear of mirrors with 512 photovoltaic modules to enslave all the mirrors independently thanks to the stepping engines installed at the end of each slats. The photovoltaic modules have been chosen to perfectly balance each slat: It is amorphous silicon thin film deposited on the cover glasses as the same thickness as the mirrors.

- Size of mirror : 0.1m×0.03m×2.42m
- Size of photovoltaic modules : 0.1m×0.03m×0.3m
- Total power peak : 475.16 W

Then, it will be possible to defocus the mirrors unilaterally to modulate the concentration and thus reduce the temperature level where necessary. In the same time, the defocused mirror may be oriented toward the incident radiation or the sky depending on the weather to produce electrical energy and store it in accumulators. The study of the spot size and its displacement on the boiler used to calculate the minimum precision stepper engines. The mirror farthest from the boiler requires a minimum precision of 1600 steps per revolution for a displacement of less than 20mm.

3.2. Primary loop

The energy produced by photovoltaic modules being sufficient, the primary loop was equipped with six three-way valves to use the four boilers in five different modes (Fig. 7). From serial mode to parallel mode, the command control can in real time, adapt the operation of the loop as the incident radiation, the heat stock status and power of the load.

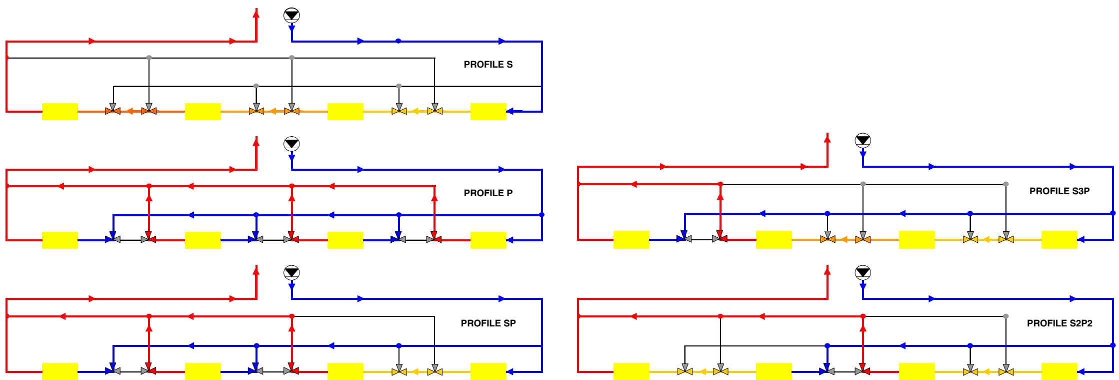

Fig. 7. The different operating modes.

3.3. The pump

To more improve the energy-temperature balance, the conventional pump was replaced by a solar pump that operates at direct current and has an integrated Maximum Power Point Tracking capable of operating in a wide range of voltage [9]. The flow can be finely adjusted after selecting the loop operating mode.

3.4. The boiler

The classic greenhouse boiler does not suite this type of system because the glass is rapidly heated when subjected to the focusing of all mirrors. This leads to a very important loss ratio. The glass will be replaced by an anti-loss structure of 15000 tubes [10] whose ratio between the diameter and height is seven [5].

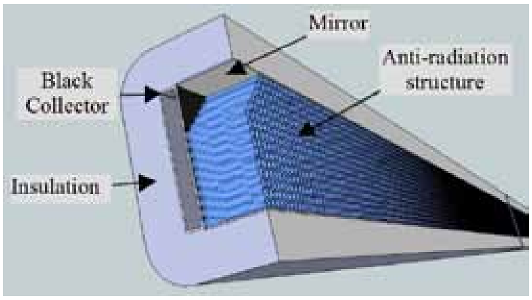

Fig. 8. Boiler with anti radiation structure.

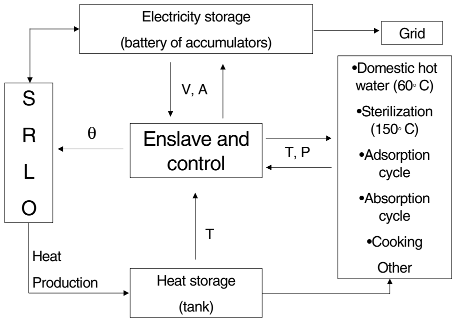

Fig. 9. Schematic view of the system

4. CONTROL AND POSSIBLE USES

Thanks to its many control possibilities, this system is able to produce energy at a constant temperature to power various loads. The temperature level reached allows making need heat but also to do cooling production.(Fig. 9)

5. Conclusion

A reflective structure that produces heat around 150°C has been upgraded. It is now able, thanks to a multiple interface control, finely optimize the energy collected and to produce sufficient electrical energy for its operation. This stand alone system becomes portable and can be deployed quickly in emergency areas. A modeling work is underway to optimize the sizing of different parts of this new system. This will improve the efficiency of PV/Th to regulate heat production and reduces energy consumption.

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